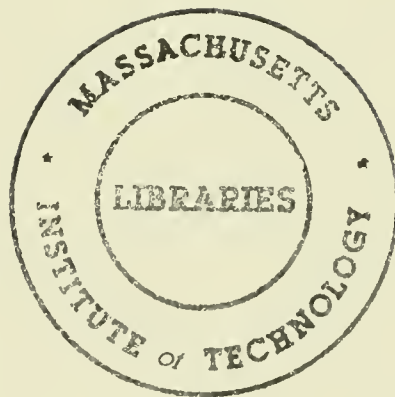
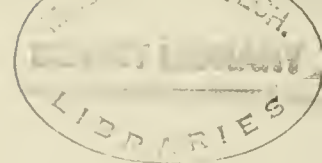


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ELECTRIFICATION, ENERGY QUALITY, AND PRODUCTIVITY
GROWTH IN U.S. MANUFACTURING

by

Ernst R. Berndt

WP#1421-83

March 1983

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IN U.S. MANUFACTURING

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I. INTRODUCTION

The effects of changing energy prices and energy availability on economic growth and productivity have been the focus of much recent research. In many such studies, energy has been incorporated as another input into production processes, along with capital, labor, and material inputs, and then substitution elasticities among inputs have been estimated.¹ In some cases, this framework has been extended to incorporate interactions between energy price increases and productivity growth. For example, in Jorgenson-Fraumeni [1981], it is found that in most U.S. industries over the 1958-1974 time period, technical change has been energy-using, which implies that energy price increases reduce the rate of multifactor productivity growth, ceteris paribus.

A rather different line of reasoning linking energy to increased productivity growth was developed shortly after World War II. Following earlier work by Herbert Simon [1950] on the effects of inexpensive nuclear-generated electricity on national income and productivity growth, Sam H. Schurr and Bruce C. Netschert [1960] undertook a detailed historical study of energy use in the U.S. economy since 1850. Schurr and Netschert advanced the hypothesis that not only had the quantity of energy been closely related to economic growth and productivity, but so also had energy quality.² One quality characteristic of energy of particular importance to energy quality was the attribute of flexibility, a characteristic embodied especially in electricity. Specifically, according to Schurr-Netschert, the flexibility of electric energy had very substantial favorable effects on industrial productivity growth, for among other features, it enabled factories to locate

machinery and equipment on the plant floors in a logical, functional manner, rather than being constrained by complicated systems of belts, pipes, and pulleys powered by steam. According to Schurr-Netschert, it was this quality attribute of flexibility that constituted a unique impact of electrification on industrial productivity growth.

The Schurr-Netschert energy quality (rather than energy quantity) hypothesis has received relatively little quantitative assessment. Nathan Rosenberg [1982,1983] has provided a number of specific examples of cost-reducing technical innovations induced partly by the flexibility of electricity, but has not attempted to provide a quantitative overview; similar historical analyses have been undertaken by Richard B. DuBoff [1967] and Warren D. Devine, Jr. [1982]. Sam H. Schurr [1982] has noted that aside from the preliminary effort by DuBoff [1966], no attempt has yet been made to quantify the importance on productivity growth of the flexibility quality attribute embodied in electric energy.³

It is worth emphasizing that the analysis of input and output quality, as distinct from their quantity, has always been a difficult issue in empirical economics. In that sense, it is not surprising that the Schurr-Netschert flexibility quality hypothesis has received so little careful empirical assessment. To obtain such an assessment, it is useful to integrate the modern demand theory of cost and production with the quality or "hedonic" literature of Zvi Griliches [1971], Sherwin Rosen [1974], and Jack Triplett [1983]. Recently, Berndt [1982] has developed further the literature linking hedonic quality analysis to the theory of cost and production,⁴ and has provided a framework to integrate these notions empirically.

In this paper, I assess the quantitative significance of the energy flexibility quality attribute on productivity growth in U.S. manufacturing, 1958-1977, using the quality-quantity demand framework presented in Berndt [1982]. According to this quality-quantity demand framework, if quality is important, it should be evident in cost-minimizing factor quantity demand equations. Moreover, economic theory provides testable parameter restrictions on the manner in which quality impacts systems of factor quantity demand equations.

The principal empirical finding reported here is that the energy flexibility quality attribute embodied in electric energy is statistically significant, but that its quantitative empirical significance over the 1958-1977 time period is rather modest. Moreover, while these energy flexibility quality effects on productivity growth may have been more important in the early and accelerating epochs of industrial electrification in the U.S., by 1958 they may already have reached a position of declining empirical significance. This latter conjecture, however, remains to be examined empirically in further research.

The paper proceeds as follows. In Section II I provide additional background details on the energy flexibility hypothesis, while in Section III I present the integrated quality-quantity theoretical framework of demand. In Section IV I discuss data and empirical results. Finally, in Section V I present brief concluding remarks.

II. ADDITIONAL BACKGROUND

In their historical study of energy use in the American economy, Sam Schurr and Bruce Netschert speculated that "...the marked acceleration in the increase in labor and capital productivity after World War I is attributed in some degree to the new methods of organizing production made possible through the growing electrification of industrial operations."⁵ When compared to steam operations, electrification offered substantial efficiency advantages to plant managers, for with flexible electric energy, machines and tools could be placed anywhere efficiency considerations dictated, and not just where belts and shafts could most easily reach them. Moreover, this flexibility facilitated the revamping of numerous industrial processes, often leading to mass production and batch-processing techniques. Richard B. DuBoff has described this phenomenon as follows:

"One of the serious disadvantages of the steam engine was that work on the plant floor had to be arranged around it, where its energy could readily reach the large power-consuming operations, not where organizational efficiency demanded. That is, several related operations might best have been grouped together; but if one of them happened to require a relatively large power input, it had to be separated from its group and placed closer to the steam engine. This dilemma did not go unnoticed during the period of steam hegemony in manufacturing. Little could be done, however, until the appearance of the electric motor, which allowed the breaking up, or fractionalization, of power machinery units. As a result, operations inside the plant could be decentralized and located more in keeping with efficiency, or flow requirements."⁶

By eliminating shafts, belts and associated needs for lubricants, fittings, and other periodic maintenance, and by reorganizing factory floors into a more functional flow process, it has been hypothesized that electrification reduced material handling and labor requirements and

thereby facilitated growth in labor productivity. Moreover, by supplying a special motor to each tool and machine ("unit drive"), and by allowing each tool to be "turned off" when not in use, energy savings were also attained by electrification; by contrast, with steam power, the entire network of boiler, engine, shafting and belts had to be run at virtual full capacity throughout the working day.

That electric power was superior to steam power in most plant operations is rather clear. However, electric energy was not cheap, especially in the early stages of electrification when central power generating units were just being constructed. But once central power stations were on stream, they provided opportunities for exploitation of economies of scale in generation. The rapid growth of industrial markets for electricity enabled utilities to exploit such scale economies further and to pass on their cost savings to industrial customers; this process was accelerated by use of promotional rate structures. An implication of these remarks is that even though central power generation was often characterized by monopoly market structures, electric power to industrial customers was priced at a rather low level. Instead of capturing potential cost savings of its customers by using a discriminatory pricing policy, electric utilities adopted pricing policies which enabled their industrial customers to capture some consumers' surplus in the form of reduced total costs, i.e., cost reductions, due to multi-factor productivity growth.⁷

In the previous paragraphs, I have attempted to summarize briefly the reasoning underlying the hypothesis that electrification of American industry has facilitated energy, labor, and multi-factor productivity growth, primarily because unlike the solid and liquid fuels, electric energy possessed the

quality attribute of flexibility. While the argument presented is eminently plausible, especially in the early stages of the electrification process, there obviously remains a need to quantify empirically this energy quality phenomenon. In turn, this requires an economic model of factor demands that distinguishes quality and quantity aspects of inputs. Hence, I now turn to a discussion of the quality-quantity factor demand model.

III. A QUALITY-QUANTITY FACTOR DEMAND MODEL

Assume there exists a well-behaved unit cost function, homogeneous of degree one in output (denoted y) that relates unit cost $c = C/y$ to the prices of $n-1$ inputs, $p_1, p_2, \dots, p_{n-1}$, to the quality-adjusted price of the n th input, p_n^* , and to time t (reflecting disembodied technical change), i.e.,

$$c = g(p_1, p_2, \dots, p_{n-1}, p_n^*, t) \quad (1)$$

It is convenient to think of p_n^* as the quality-adjusted price of energy, where quality depends on a number of physical attributes such as volatility, cleanliness, flexibility, amenability to storage and mass. Denote the vector of such quality attributes as z_n , and define a scalar index of quality for the n th input as b_n , i.e.,

$$b_n = h_n(z_n) \quad (2)$$

To understand better the notion of quality, I now introduce the notion of conversion ratios. First, define the production function corresponding to (1) as

$$y = G(x_1, x_2, \dots, x_n, b_n, t) \quad (3)$$

where b_n is the quality index associated with the input quantity x_n .

Corresponding to each level of quality b_n , one can solve (3) to obtain the input requirement function for x_n :

$$x_n = f(y, x_1, x_2, \dots, x_{n-1}, b_n, t) \quad (4)$$

Now compare the different required quantities of x_n corresponding to alternative quality levels b_{no} and b_{n1} :

$$\frac{x_{no}}{x_{n1}} = \frac{f(y, x_1, x_2, \dots, x_{n-1}, b_{no}, t)}{f(y, x_1, x_2, \dots, x_{n-1}, b_{n1}, t)} \quad (5)$$

Following Lawrence J. Lau [1982], Berndt [1982] interprets the ratio x_{no}/x_{n1} as the conversion ratio between two different quality levels of the n th input.

Suppose now that one wishes to obtain a quality-adjusted measure of x_n by writing x_{no} in terms of x_{n1} , that is to say, measure x_{no} with quality b_{no} in terms of the quantity x_{n1} having quality level b_{n1} . This can be envisaged as measuring energy quantity x_{no} with energy quality (say, flexibility) level b_{no} in terms of the energy quantity level x_{n1} having

quality level b_{n1} . The quantity of x_{no} in terms of its equivalent quantity in terms of x_{n1} is given by rewriting (5) as:

$$x_{no}^* = \frac{f(y, x_1, x_2, \dots, x_{n-1}, b_{no}, t)}{f(y, x_1, x_2, \dots, x_{n-1}, b_{n1}, t)} \cdot x_{n1} \quad (6)$$

Next, consider the output y^* that could be produced with these x_{no}^* units having quality level b_{no} , given by:

$$y^* = G(x_1, x_2, \dots, x_{no}^*, b_{no}, t) \quad (7)$$

and compare this y^* with the output y' obtained by utilizing quantity level x_{n1} having quality level b_{n1} ,

$$y' = G(x_1, x_2, \dots, x_{n1}, b_{n1}, t) \quad (8)$$

Lau [1982, p. 177] has shown that these two outputs are precisely equal, i.e., $y^* = y'$. An important implication of this seemingly obvious result is that not only does one have a way of quality-adjusting an input in terms of a standard unit consistent with demand theory, but these equivalent units can also be used in a production (or cost) function defined in terms of the standard unit.

Essentially, the task served by the conversion ratio (5) and the quality-adjustment expression (6) is to standardize the various qualities into a common unit of measurement. A non-trivial feature of this quality adjustment is that up to a factor of proportionality the various quality-rated x_n (say, energy types) are constructed to be perfect substitutes for one

another; note, however, that the proportionality factor b_n can vary and will depend on the physical characteristics z_n (see (2)) such as energy flexibility.

Any empirical implementation of this quality-quantity approach requires careful specification of the conversion function (5) or the quality adjustment measures in (6). Note that in (6), the quality-adjustment factor in square brackets is a function of $y, x_1, x_2, \dots, x_{n-1}, t$. As Lau and Berndt have noted, an important special case occurs when the conversion function is specified to be independent of $y, x_1, x_2, \dots, x_{n-1}, t$, for in such a case, the production function must assume the multiplicative factor augmentation form⁸

$$Y = G(x_1, x_2, \dots, x_{n-1}, b_n \cdot x_n, t). \quad (9)$$

Moreover, in this case the dual cost function has the form (see Lau [1982], pp. 180-182):

$$c = H(p_1, p_2, \dots, p_{n-1}, p_n/b_n, t) \quad (10)$$

Note that in (9), the quality-adjusted quantity is $x_n^* = b_n \cdot x_n$, while in (10) the quality-adjusted price $p_n^* = p_n/b_n$, where p_n is the price of x_n unadjusted for quality and $b_n = h(z_n)$. Hence price times quantity is invariant to quality adjustment.

Having expressed quality adjustment in terms of multiplicative factor augmentation functions, I now relate the quality conversion specification to the widely-used hedonic price equations. Given the conversion function (5),

the prices of the different (x_n, b_n) quality-quantity combinations must, under the assumption of cost-minimization, be in proportion to their marginal productivities, i.e., the effective or quality-adjusted price per unit of the standardized quality x_n , $p_n/b_n = p_n^*$, must be equalized at the margins, so that

$$\frac{p_{no}}{b_{no}} = \frac{p_{n1}}{b_{n1}} = p_n^* \quad (11)$$

where p_n^* is a "base price" constant reflecting the price of the standardized, quality-adjusted unit. Taking logarithms of (11), I obtain the hedonic price equation

$$\ln p_{n1} = \ln p_n^* + \ln b_{n1} \quad (12)$$

which from (2) relates, for example, the quality unadjusted price $\ln p_{n1}$ to the quality-adjusted price $\ln p_n^*$ and the physical quality characteristics z_n , i.e.,

$$\ln p_{n1} = \ln p_n^* + \ln h(z_{n1}) \quad (13)$$

Hence, the hedonic price equation (13) converts the characteristics z_{n1} (such as energy flexibility) embodied in x_{n1} into "base price" or effective price units, which can then be inserted into the standardized quality cost function (10).

I implement this quality-quantity demand model as follows. First, I ignore all other energy quality factors and focus only on energy flexibility, denoted hereafter as F , i.e.,

$$b_n = h(F) \quad (14)$$

I define F as the proportion of total energy consumption E taken in the terms of electricity (denoted $ELEC$), i.e.,

$$F \equiv ELEC/E \quad (15)$$

where E is a Divisia quantity index of energy types.⁹ Note that this particular definition of energy flexibility assumes that all non-electric fuels are inflexible. In future work, one may want to examine implementing a rank-ordering scheme with electric energy as the most flexible, next the liquid and solid fuels, and finally, natural gas, and then assign each with weights based on engineering cost calculations.

I then specify the hedonic price-quality adjustment equation to have the double-logarithmic form

$$\ln P_{Et} = \ln P_{Et}^* + b_{EF} \ln F_t, \quad t=1, \dots, T \quad (16)$$

where P_{Et} is the quality-unadjusted price of energy, $\ln F_t$ is the extent of flexibility (electrification), and P_{Et}^* is the quality-adjusted price of energy, all at time t . Intuitively, one can envisage $\ln P_{Et}^*$ as a residual in a regression equation--it reflects the price of energy once it is

"corrected" or "purged" of quality changes. Obviously, to the extent that flexibility improves energy quality, $b_{EF} > 0$. Later, it will be convenient to re-write (16) as follows:

$$\ln P_{Et}^* = \ln P_{Et} - b_{EF} \ln F_t \quad (17)$$

Regarding the cost function (1) and (10), I specify it to have the translog form in quality-adjusted prices,

$$\begin{aligned} \ln c = \ln \alpha_0 + \sum_i \alpha_i \ln P_i + \alpha_t \cdot t + \frac{1}{2} \sum_{ij} \gamma_{ij} \ln P_i \ln P_j \\ + \sum_i \gamma_{it} \cdot t \cdot \ln P_i + \frac{1}{2} \gamma_{tt} \cdot t^2 \end{aligned} \quad (18)$$

where the subscripts i, j refer to P_K, P_L, P_E^* and P_M , which in turn refer to prices of capital services (P_K), labor services (P_L), quality-adjusted energy (P_E^*) and non-energy intermediate materials (P_M). Symmetry and homogeneity of degree one in input prices imply the following parameter restrictions on (18):

$$\begin{aligned} \sum_i \alpha_i = 1, \gamma_{ij} = \gamma_{ji}, \sum_j \gamma_{ij} = \sum_i \gamma_{ij} = 0, \\ \sum_i \gamma_{it} = 0 \end{aligned} \quad (19)$$

Use of Shephard's Lemma yields the cost-minimizing share equations

$$S_i = \frac{\partial \ln c}{\partial \ln P_i} = \frac{P_i X_i}{cY} = \alpha_i + \sum_j \gamma_{ij} \ln P_j + \gamma_{it} \cdot t, \quad i=1, \dots, n \quad (20)$$

When (17) is substituted into (20), this generates the equation system:

$$\begin{aligned}
 S_K &= \alpha_K + \gamma_{KK} \ln P_K + \gamma_{KL} \ln P_L + \gamma_{KE} \ln P_E - \gamma_{KE} b_{EF} \ln F + \gamma_{KM} \ln P_M + \gamma_{Kt} \cdot t \\
 S_L &= \alpha_L + \gamma_{LK} \ln P_K + \gamma_{LL} \ln P_L + \gamma_{LE} \ln P_E - \gamma_{LE} b_{EF} \ln F + \gamma_{LM} \ln P_M + \gamma_{Lt} \cdot t \\
 S_E &= \alpha_E + \gamma_{EK} \ln P_K + \gamma_{EL} \ln P_L + \gamma_{EE} \ln P_E - \gamma_{EE} b_{EF} \ln F + \gamma_{EM} \ln P_M + \gamma_{Et} \cdot t \\
 S_M &= \alpha_M + \gamma_{MK} \ln P_K + \gamma_{ML} \ln P_L + \gamma_{ME} \ln P_E - \gamma_{ME} b_{EF} \ln F + \gamma_{MM} \ln P_M + \gamma_{Mt} \cdot t
 \end{aligned}
 \tag{21}$$

Note that the quality adjustment parameter b_{EF} appears in each of the four share equations, along with the flexibility variable $\ln F$, and that this implies cross-equation restrictions on the estimated parameters. Hence, the quality-quantity framework presented here generates testable parametric restrictions.

Following Jorgenson-Fraumeni [1981], one can also differentiate the unit cost function (18) with respect to t , thereby obtaining the cost-diminution equation

$$\frac{\partial \ln c}{\partial t} = \frac{\dot{c}}{c} = \alpha_t + \gamma_{Kt} \ln P_K + \gamma_{Lt} \ln P_L + \gamma_{Et} \ln P_E - \gamma_{Et} b_{EF} \ln F + \gamma_{Mt} \ln P_M + \gamma_{tt} \cdot t \tag{22}$$

As has been noted elsewhere, (22) is interpreted as the negative of the rate of multifactor productivity growth; it indicates the rate of cost diminution due to disembodied technical change, holding input prices fixed. Hence, if multifactor productivity growth is positive, $\dot{c}/c$ in (22) will be negative. Note that according to (22), the rate of multifactor productivity growth depends on the quality (flexibility) of energy. Specifically,

$$\frac{\partial \dot{c}/c}{\partial \ln F} = -\gamma_{Et} b_{EF} \tag{23}$$

Equation (23) merits special attention. Earlier, I noted that the quality effect of flexibility on energy is captured by b_{EF} in (16), and that if flexibility is important to quality in a factor demand model, b_{EF} should be positive. But what of γ_{Et} in (23)? According to (21), the γ_{it} terms in the share equation system reflect the bias of technical change; specifically, technical change is said to be input i -using, -saving, or -neutral as γ_{it} is positive, negative, or zero, respectively. Hence, the γ_{it} parameter reflects the relative impacts of technical progress; while technical progress might reduce the demand for all inputs, it may not do so equi-proportionally. When γ_{it} is positive, for example, technical progress may result in savings for input i less than the average of all factors.¹⁰ Moreover, as has been emphasized by Jorgenson-Fraumeni, when technical change is input- i using (i.e., $\gamma_{it} > 0$), then increases in P_i reduce the rate of multifactor productivity growth, ceteris paribus, i.e., the rate of cost diminution is reduced, for from (22)

$$\frac{\partial \dot{c}/c}{\partial \ln P_i} = \gamma_{it} \quad (24)$$

With this background, I now interpret (23) as follows. Note that b_{EF} is expected to be positive, and that according to (23) increases in F result in further cost diminution only if γ_{Et} is positive. But with γ_{Et} positive, increases in energy prices reduce the rate of multifactor productivity growth. However, increases in electrification or energy flexibility by (17) in fact reduce the quality-adjusted price of energy (or at least mitigate the increase in P_{Et}^*), and thereby result in increased rates of cost diminution, ceteris paribus. In summary, therefore, since b_{EF}

> 0 , multifactor productivity growth will be increased, unaffected or decreased ($\partial c/c/\partial \ln F$ will be negative, zero or positive, respectively) as γ_{Et} is positive, zero, or negative. Note that when technical change is energy-neutral ($\gamma_{Et} = 0$), increases in energy quality have no effect on multifactor productivity growth.

Another way of looking at the effects of electrification is more direct. Instead of examining the rate of cost diminution equation (22), one might look directly at the overall impact by computing the elasticity of unit cost with respect to electrification; this turns out to be

$$\frac{\partial \ln c}{\partial \ln F} = \frac{\partial \ln c}{\partial \ln P_E^*} \cdot \frac{\partial \ln P_E^*}{\partial \ln F} = - S_E \gamma_{Et} b_{EF} \quad , \quad (25)$$

i.e., it is the rate of cost diminution effect in (23) weighted by the cost share of energy S_E . When the cost share of energy is small, this elasticity can also be expected to be small.

In the above paragraphs, I have examined the effects of electrification on unit costs and on multifactor productivity growth, effects that have been hypothesized by Schurr and others to be favorable. However, it has also been argued by Schurr-Netschert that increases in electrification improved labor productivity growth. To assess this possible phenomenon analytically, I first note that from (21) one can re-write $S_L = P_L L/cY$ in labor productivity terms as

$$Y/L = P_L/S_L \cdot c \quad (26)$$

The effects of electrification on labor productivity growth can be obtained by taking logarithms in (26) and differentiating,

$$\frac{\partial \ln(Y/L)}{\partial \ln F} = \frac{\partial \ln P_L}{\partial \ln F} - \frac{\partial \ln S_L}{\partial \ln F} - \frac{\partial \ln c}{\partial \ln F} \quad (27)$$

which by (21) and (25) yields

$$\frac{\partial \ln(Y/L)}{\partial \ln F} = b_{EF} \left(-\frac{\gamma_{LE}}{S_L} + S_E \gamma_{Et} \right) \quad (28)$$

Since γ_{LE} represents the share elasticity of labor with respect to energy price changes, the total effect of electrification on labor productivity growth can be interpreted as the electrification-induced labor substitution effect ($b_{EF}\gamma_{LE}/S_L$) plus the electrification-induced multifactor productivity effect ($b_{EF}S_E\gamma_{Et}$). Note that while S_L and S_E are positive and b_{EF} is also expected to be positive, (28) can be positive or negative, depending on the signs of γ_{LE} and γ_{Et} .

Similar expressions can be derived for the effects of electrification on energy, capital, and non-energy intermediate material productivity growth. These turn out to be:

$$\frac{\partial \ln(Y/E)}{\partial \ln F} = b_{EF} \left(\frac{\gamma_{EE}}{S_E} + S_{EY_{Et}} \right), \quad (29)$$

$$\frac{\partial \ln(Y/K)}{\partial \ln F} = b_{EF} \left(\frac{\gamma_{KE}}{S_K} + S_{EY_{Et}} \right), \text{ and} \quad (30)$$

$$\frac{\partial \ln(Y/M)}{\partial \ln F} = b_{EF} \left(\frac{\gamma_{EM}}{S_M} + S_{EY_{Et}} \right), \quad (31)$$

To summarize, in this section I have presented a quality-quantity factor demand model that permits quantification of the effects of increased electrification (improved energy quality) on the level of costs, the rate of multifactor productivity growth, and the rates of labor, energy, capital, and material productivity levels. It is worth emphasizing again that if the quality-quantity distinction is important for energy, then in this model, it must manifest itself in the system of cost-minimizing demand functions (21) by generating parameter estimates of b_{EF} that are positive and significantly different from zero. Moreover, the incorporation of energy quality into demand equations generates testable cross-equation parameter restrictions. If the energy quality-quantity distinction is not important, then it should have no effect on factor demand equations, i.e., b_{EF} should be zero. Thus, the question of whether energy quality is important is a testable, empirical proposition.

IV. DATA AND EMPIRICAL IMPLEMENTATION

The data used in the empirical implementation are for the total U.S. manufacturing sector over the time period 1958-1977. Although data for a longer and earlier time period would have been preferable, at the present time consistent series for these variables over time are not available. The

1958-1977 data used here have the advantage, however, of including periods of both rising and falling energy prices, and have been analyzed using somewhat different techniques. Specifically, the data on prices and quantities for K,L,E,M, and Y have been published in J. Randolph Norsworthy and Michael J. Harper [1981]¹¹; data on ELEC have graciously been made available by Norsworthy-Harper. The resulting series on $F \equiv \text{ELEC}/E$ has been calculated; figures for the 1958-1977 time period are presented in Table 1. Note that over this time period, energy quality F increased by about 32%, or about 1.5% per year; average annual growth in F declined since 1973, however, from 1.6% in 1958-1973, to 0.9% in 1973-1977.

I have estimated the equation system consisting of the unit cost function (18) and three of the four linearly independent share equations (21), with the restrictions (19) imposed, using the method of maximum likelihood, under the assumption that the additive disturbance vector is multivariate normally distributed with mean vector zero and nonsingular covariance matrix. Results of the estimation are presented in Table 2.

As is seen in Table 2, the estimated value of the energy quality coefficient is .7567, with an asymptotic t-statistic of 5.75, which is considerably larger than the 0.05 critical value of 1.96. The null hypothesis that $b_{EF} = 0$ is also rejected using a likelihood ratio test; here the test statistic is 12.74 while the 0.05 (0.01) chi-square critical value is 3.84 (6.63). Hence there is strong evidence here in support of the notion that both the quality and the quantity of energy are important to factor demand systems in U.S. manufacturing.¹²

Table 1

Values of the Energy Flexibility Index for U.S. Manufacturing, 1958-1977

Year	F	Year	F	Year	F	Year	F
1958	1.00000	1963	1.03311	1968	1.11185	1973	1.27339
1959	1.01023	1964	1.04065	1969	1.14157	1974	1.23585
1960	1.00734	1965	1.05689	1970	1.15852	1975	1.26507
1961	1.01095	1966	1.08764	1971	1.15860	1976	1.26335
1962	0.99426	1967	1.13488	1972	1.20195	1977	1.31842

Source: J. Randolph Norsworthy and Michael J. Harper [1981], unpublished underlying tables.

TABLE 2

Maximum Likelihood Parameter Estimates of Energy Flexibility
Model for U.S. Manufacturing, 1958-1977
(Asymptotic t-statistics in parentheses)

Parameter	Estimate	Parameter	Estimate	Parameter	Estimate
α_o	.1622 (19.44)	γ_{KK}	.0703 (21.09)	γ_{EM}	-.0231 (7.92)
α_K	.1147 (61.04)	γ_{KL}	-.0048 (1.05)	γ_{MM}	.2818 (16.43)
α_L	.3451 (68.93)	γ_{KF}	-.0041 (8.15)	γ_{Kt}	-.0003 (2.41)
α_E	.0164 (19.58)	γ_{KM}	-.0615 (11.00)	γ_{Lt}	-.0044 (15.12)
α_M	.5238 (102.3)	γ_{LL}	.1964 (14.21)	γ_{Et}	.0002 (2.35)
α_t	0.0152 (8.96)	γ_{LE}	.0056 (2.56)	γ_{Mt}	.0045 (14.60)
b_{EF}	.7567 (5.75)	γ_{LM}	-.1972 (13.98)	<u>Other</u> $\frac{1}{\ln L} = 388.709$	
γ_{tt}	.0007 (4.35)	γ_{EE}	.0216 (22.55)		

Earlier I noted that the economic theory of cost and production generates testable parameter restrictions on the way in which quality variables enter the factor demand equations. To test these restrictions empirically, I have estimated the cost share equation system (21) with and without the multiplicative restrictions on the $\ln F$ coefficients in (21) imposed. The likelihood ratio test statistic is 1.87, while the .05 chi-square critical value is 5.99. Hence, the parametric restrictions on the energy quality variable, implied by economic theory, cannot be rejected. These results therefore provide empirical support for the quality-quantity model specification.

The effect of electrification on multifactor productivity growth has been shown in (23) to depend critically on whether technical change was energy-neutral, i.e., on whether $\gamma_{Et} = 0$. As seen in the last column of Table 2, the estimated value of γ_{Et} is small and positive, 0.0002, but statistically significant--the asymptotic t-statistic is 2.35. A joint likelihood ratio test was also performed to test for Hicks-neutrality, i.e., $\gamma_{Et} = \gamma_{Lt} = \gamma_{Kt} = \gamma_{Mt} = 0$. Here the test statistic was 110.662, while the .01(.05) chi-square critical value for the three linearly independent restrictions is 7.81 (11.3). Hence, the null hypothesis of Hicks-neutrality is decisively rejected.

Together the estimated positive values of b_{EF} and γ_{Et} imply by (23) that increases in electrification reduced costs and increased multifactor productivity, albeit very modestly. Specifically, the estimated elasticity of cost diminution with respect to electrification is calculated using (23) to be -.00012. Using (25), the estimated elasticity of unit cost with respect to

electrification is the above number multiplied by S_E , which in this case is only 2.45% of (23), i.e., $-.000003$.

To place these numbers in perspective, I have calculated predicted unit costs over the 1958-1977 time period, (i) using historical values for F , (ii) using the 1958 value of F throughout the 1958-1977 period, and (iii) using the 1958 value of $ELEC$ throughout the 1958-1977 time period. The second calculation assumes that no further relative electrification took place after 1958, i.e., the ratio $ELEC/E$ remained constant. The last calculation assumes the absolute level of $ELEC$ remained constant while E increased; by 1977 the implied value of F in such a case would have been 0.493. In 1977, had electrification remained at its 1958 relative level, total unit costs would have been 0.56% smaller, while if electrification had remained at its 1958 absolute level, unit costs would have been 2.45% smaller. Hence, it is clear that the effects of electrification on multifactor productivity growth during this time span are small.

The story is somewhat different, however, when it comes to effects of electrification on labor and on energy productivity growth. Using (28) and (29), I calculate elasticities of average labor and average energy productivity, respectively, with respect to relative electrification. For 1977, these turn out to be 1.7% and 44.2%, respectively. Had F remained at its 1958 level in 1977 (instead of increasing about 32%), labor productivity in 1977 would have been about 1.04% lower, while energy productivity in 1977 would have been about 16% lower. Had electrification remained at its 1958 absolute value with F falling to 0.493, in 1977 labor productivity would have been 5.07% lower while energy productivity would have fallen 53%, i.e.,

considerably more non-electric energy would have been required to replace the high-quality electric energy.

I conclude, therefore, that increases in electrification 1958-1977 in U.S. manufacturing had a very small positive effect on multifactor productivity growth, a modest positive effect on labor productivity growth, and a somewhat larger impact on energy productivity growth. These empirical findings are consistent with the Schurr-Netschert hypothesis.

V. Summary and Concluding Remarks

A number of energy analysts have hypothesized that the flexibility of electricity relative to liquid and solid fuels has had an important positive impact on productivity growth. Accordingly, the purpose of this paper has been to obtain quantitative estimates of the effect of energy flexibility on the rate and level of industrial productivity growth. Because energy flexibility is a quality attribute of energy, to address this issue it has been necessary to employ a model of factor demands consistent with the theory of cost and production that distinguishes input quality from input quantity. Using such a model, I have found that energy quality, specifically the electrification ratio in total energy, has had a positive and statistically significant impact on productivity growth in U.S. manufacturing over the 1958-1977 time period. While this energy quality effect is very small for multifactor productivity growth, it is modest for labor productivity growth, but is of considerable importance for energy productivity. These findings are gratifying and suggest that the quality-quantity demand framework can be

usefully employed to address issues heretofore not amenable to quantification, even at the aggregate manufacturing level.

A number of further research projects are suggested by this study. For example, alternative weighting schemes for the various energy types could be constructed in order to develop alternative measures of energy flexibility, and then their relative impacts on productivity growth could be assessed. Perhaps even more important, however, would be the development and estimation of a data base that included years prior to 1958, a period in the history of U.S. industry when electrification proceeded at a much more rapid pace. Analysis of the 1880-1958 time period would provide much useful information on the Schurr-Netschert energy flexibility hypothesis.

FOOTNOTES

1. See, for example, Berndt-Jorgenson [1973], Jorgenson-Fraumeni [1981], and Berndt-Wood [1982].
2. See especially pp. 185-189, in Schurr-Netschert [1960].
3. While studies such as that by Berndt-Fuss-Waverman [1980] and Jorgenson [1983] disaggregate energy into electric and non-electric types, they do not focus attention directly on the energy quality attribute of flexibility.
4. Berndt's work draws on earlier related research by Lawrence J. Lau [1982] and John Muellbauer [1975]. For additional references, see Berndt [1982].
5. Schurr-Netschert [1960], p. 189.
6. DuBoff [1967], p. 514.
7. For a discussion of market structure and the distribution of benefits of product innovations, see F.M. Scherer [1980], especially pp. 442-443.
8. The multiplicative representation does not, however, necessarily require that the conversion function be independent of $y, x_1, x_2, \dots, x_{n-1}, t$. See Lau [1982, pp. 177-78] and Berndt [1982, Sections II and III].
9. For further discussion of energy and Divisia aggregation, see Berndt [1978].
10. For further discussion, see Berndt-Wood [1982].
11. These data have also been used in the study by Berndt [1980].
12. I also estimated the hedonic equation (16) directly (adding an intercept term) by least squares. This procedure ignores, of course, the interrelations within the factor demand system (21). The estimated value of b_{EF} was 1.190, with a t-statistic of 3.74.

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